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Division of Thermonuclear Fusion Research,
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An application of the LHRF heating to a large tokamak is investigated. A frequency of 2.0 GHz is selected for a INTOR plasma. Numerical simulation of the LHRF heating shows the importance of the real time feed back of the RF parameters of phase difference, power and frequency corresponding to the plasma parameters in a large tokamak.

Keywords: Tokamak, INTOR, RF Heating, Simulation, High-frequency Heating LHRF

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*) Institute of Plasma Physics Laboratory, Nagoya Univ., Nagoya.

ＩＮＴＯＲにおける低域混成波帯の高周波加熱の数値解析

日本原子力研究所東海研究所核融合研究部
今井　剛・岡本　正雄*・永島　孝

（1981年12月11日受理）

大型トカマクへのＬＨＲＦ（低域混成波帯）の高周波加熱の適用につき，ＩＮＴＯＲを例にとり，検討を行った。ＩＮＴＯＲのプラズマパラメータに対しては，2.0 GHz が適当である。これを用いて加熱のシュミレーションを行った結果，導波管相互の位相差，ＲＦ・パワー，及び周波数のプラズマパラメータに応じた，実時間フィードバックの必要性が，明らかとなった。

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1. Introduction

RF heating is very attractive as the further heating method of a plasma in a tokamak reactor, because of its engineering simplicity compared with NBI. Recently, many experimental results which demonstrated the effectiveness of RF heating in tokamaks have been reported [1-3]. As for the lower hybrid range of frequencies (LHRF) heating, though some harmful nonlinear effects like parametric instabilities and ion tail formation near the plasma edge have been reported, they will be reduced in a hot dense plasma in future large tokamak. Results in the JFT-2 and possibly Alcator A showed good heating efficiency [2]. Moreover, LHRF have shown several experimental successes in a current drive [4]. There are many other experiments which support the feasibility of the LHRF heating in future large tokamaks. Because of these encouraging results and the engineering superiority, LHRF heating with 10 MW of RF power will be done in the JT-60. When we think of the terribly bad environment around the reactor, engineering simplicity of the wave launching system like the LHRF heating is extremely attractive. It is natural choice to take the LHRF heating as one of the prospective further heating methods in INTOR.

Brief review of the LHRF heating will be given in the section 2. Numerical study including a simulation of the LHRF heating in INTOR is described in the section 3. In the final section, we propose the recommendation of the RF system for INTOR, as the conclusion of this report.

2. Brief Review of the LHRF Heating

Lower hybrid resonance frequency is the ion plasma frequency in the space filled with the magnetically constrained electrons. Therefore, LHRF heating is sensitive to the ion density just like as that ICRF and ECH are sensitive to the magnetic field. Before the arrival of the lower hybrid wave (LHW) to the resonance point, there are several processes which the wave must experience.

At first, the wave is launched from the outside of plasma. In the LHRF, waveguides, which are attractive in a reacor environment and easy to be formulated theoreticaly, are possible to use. Electromagnetic wave radiated from the launcher couples to the slow wave at the edge and propagates to the interior in the linear theory of the LHW. It is well known that a slow wave must satisfy the accessibility condition in order to penetrate further inside. The accessibility is approximately given as $N_z > 1 + \omega_{pe}^2/\omega_{ce}^2|_{res}$, where $|_{res}$ denotes the value at the lower hybrid resonance point [5]. After the penetration into the core of plasma, the wavelength become shorter. The wave

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Almost every LHRF heating experiment has predicted the necessity of the accessibility condition and the turning point of the LHW [2]. From these prediction, we can easily find the importance of the penetration of the LHW into the core plasma and mode conversion to the short wavelength ion waves. Since the linear damping mechanism like ion cyclotron harmonic damping and Landau damping saturate easily at low power, the ion wave accumulates in the core plasma and nonlinear stachastic heating is expected to occur near the turning point [7].

Heating efficiency of the LHRF (1.5 ~ 3.0 eV/kW) is moderate, compared with the other heating schemes like NBI, ICRF and ECH (3 ~ 6 eV/kW) in the present grade tokamak experiments. As mentioned before, this reduction of the heating efficiency is mainly due to the surface absorption which will be probably suppressed in the reactor plasma and a ripple loss or an orbit loss of perpendicular energetic ions which will also be confined in the reactor plasma. Thus the LHRF heating will be expected to work well in the reactor plasma like INTOR. Weak point of the LHRF heating in the present time is the lack of the experiments to demonstrate the excellent heating efficiency. Coming experiments of the LHRF heating in the PLT, Alcator C, JFT-2M, Wega, Asdex and JT-60 will clarify the present ambiguity soon.

3. Numerical Studies of the LHRF Heating in INTOR

3.1 Design of the RF parameters

First of all, it is necessary to determine the basic RF parameters for INTOR. For this purpose, behavior of the LHW in a plasma parameter is converted to the hot ion wave due to the thermal effect of ions and is absorbed near the turning point via the ion cyclotron harmonic damping and/or Landau damping. Above linear heating model is very simple and easy to understand, but the experimental results are somehow different from it. It seems to be indispensable to apply nonlinear consideration to understand the experimental results. There are many nonlinear theory of the LHW. Among them, parametric instabilities and nonlinear stochastic heating are very plausible. Parametric instabilities were observed in every LHRF heating experiment in tokamaks. But the role of them seems to be a mechanism of surface heating. Some attempt to reduce parametric instabilities near the surface have been made [6]. In the reactor grade tokamak parameters, this surface absorption will not be serious problem, since the ratio of the RF power density and plasma energy density $R_N = S^{RF}/nT$ will be a few hundredths of that of the present experiments.

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3. Numerical Studies of the LHRF Heating in INTOR

3.1 Design of the RF parameters

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The expected plasma parameters of INTOR are peak plasma density n_{e0} = $1.5 \sim 2.0 \times 10^{20}$ m^{-3}, the toroidal field B_t = 5.5 T and <T> = 10 keV. Therefore, the frequency f = 2.0 GHz and the refractive index parallel to the toroidal field $N_z \simeq 2$ is the first choice for ion heating in INTOR.

Next, the launching structure of the LHW must be determined. For the engineering simplicity, number of waveguides should be small and the effective area to radiate the RF power should be large. But for the optimization of the wave penetration and absorption, large number of the waveguides and small width of the each waveguide in the toroidal direction (b) make a good N_z-spectrum for heating. It is the most important to harmonize the above competing requirements in order to get a good heating result in a large machine. We select a phased array of 8 (array) x 6(story) waveguides with each size of the wave guide b = 30–40 mm x a = 125 mm. The required port size is 0.7 m poloidally and 1.1 m toroidally. Reflection of the launcher with b = 35 mm vs phase difference between the adjacent waveguides $\Delta\phi$ is shown in Fig. 2 , which is calculated from Brambilla theory [8]. Good coupling is obtained in $\Delta\phi$ = 120° ~ 180°. Power spectra $P(N_z)$ are also calculated corresponding to these phasings, in Fig. 3. It is seen that the peak N_z is variable from 1.2 to 1.8, by changing the phasing $\Delta\phi$. As shown in Fig. 1, the accessibility condition is very severe, it requires $N_z > 1.6$ near the plasma center with a peak density n_{e0} = $1.5 \times 10^{20} m^{-3}$.

Plasma parameters of INTOR change in time. The plasma density is expected to increase from $\bar{n}_e = 0.4 \times 10^{20}$ m^{-3} to 1.4×10^{20} m^{-3}, the plasma current I_p = 4 to 6 MA, and the temperature <T> = 1.0 to 10.0 keV. As the lower hybrid frequency is sensitive to the density and it is approximately proportional to the square root of the density, increase in the density by factor of 3 requires that in the frequency by 1.7. Thermal correction of the LHRF also requires frequency upshift with increase in an ion temperature. Control of the phasing of the launcher provides a part of the solution to these variation of plasma parameters. But it is impossible to follow to the all parameters in INTOR only by changing the phasing within the framework of the linear theory, if the choice of the frequency is only one point.

To see the effect of these variation, the profiles of the deposited RF power are calculated within the framework of linear theory, which is shown in Fig. 4. Change of density by factor of 1.4 brings the out shift of the profile of the deposition from $0 \leq r/a \leq 0.3$ to $0.3 \leq r/a \leq 0.4$. Therefore, if the profile of the depostion is optimized in the initial stage of the discharge, it become surface heating even in the middle of the discharge. The same out shift occurs in the case of the variation of the ion temperature, which is shown in Fig. 5. As far as wave deposition profile obeys to the linear damping mechanism, some frequencies to tune or several power sources of different frequencies, corresponding to the dynamicaly changing parameters, are required to keep the core heating.

As described in the section 2, the results of the present experiments did not agree with the linear theory well. Nonlinear stochastic heating plausibly dominates the ion heating. In this case, wider density window to heat ions may be expected [7,9]. But we must be careful whether this wide density window is only specific result in small and/or low I_p tokamaks. This question should be clarified in coming experiments of LHRF in medium size and large I_p tokamaks.

3.2 Simulation

To veryfy the validity of the selection of the RF parameters, numerical simulation of the LHRF heating in INTOR is performed in both cases of linear and simplified nonlinear stochastic models [9]. Tokamak transport code is one dimensional fluid model, where Maxwell and energy balance equations are solved. Detailes of the tokamak code is described in ref. 10. In the heating code, power spectrum from the launcher and the trajectry and damping of each N_z wave are calculated.

In the simulation, we assume the plasma density is almost constant for simplicity. Time evolutions of ion temperature in the cases of the linear and nonlinear stochastic model are shown in Fig. 6(a) and (b), respectively, where RF parameters are f = 2.0 GHz, b = 35 mm, $\Delta\phi$ = 180°, N_{WG} = 8 and P_{RF} = 50 MW. In the case of the linear model, ion temperature at the center increases fast in the early time of the RF pulse and saturates soon at about 5 keV. On the other hand, the results of the nonlinear model is quite different. Ion temperature near the center increase gradually and does not saturate during the RF pulse of about 10 seconds. It increases from 3 to about 20 keV, which is the adequate temperature for INTOR. Reason of this difference between the two model is figuratively seen in Fig. 7(a) and (b), where the time change in the profiles of ion temperature are shown in the both cases. At the initial time of the RF pulse in Fig. 7(a), deposition profile of the RF power is optimezed, so that the resultant ion temperature peaks at the center, but the profile is widened soon and the deposition region shifts outward, which make the hollow ion temperature profile. This hollow peak of the ion temperature blocks the RF power to penetrate further into the core plasma. On the other hand, in the case of nonlinear stochastic model, the change of the deposition profile due to that of the ion temperature is quite small. Therefore plasma ions are heated very well up to 20 keV, as shown in Fig. 6(b) and Fig. 7(b), which suggests that we must have a measure to keep the optimized deposition of the RF power. It should be noted, here, α particle heating is not taken into consideration in this code. If the α particle heating is added, more enhancement of the ion temperature is expected in the both cases.

4. Recommendation of the RF System

From the previous studies in the section 3, it is found that only one choice of the RF parameters of ($f, \Delta\phi$) can not heat a plasma to the required temperature for fusion. It seems to be indispensable to take a feed back control of RF power, phase and frequency to optimize the deposition profile in accordance with a change in density and temperature. If the deposition profile is controlled well by the feed back or pre-programming of the RF parameters, it is possible to heat a plasma to an adequate temperature for fusion as seen from Fig. 7(b). Therefore, we strongly recommend the full feed back LHRF system for INTOR. It will provide an efficient ion heating to the INTOR, which has the wide range of plasma parameters.

Block diagram of the LHRF system with the feed back control is shown in Fig. 8. It is relatively easy to develope the low power section of wide frequency band with full feed back function of RF power P_{RF}, phasing $\Delta\phi$ and frequency f, since we have already had highly developed electronics in this field. Difficulties in the RF system in Fig. 8 are developements of high power (> 1 MW), almost cw and wide band ($f_0 \pm 15\%$) klystron and microwave circuits like a 3 dB coupler and a phase shifter. Circulator is excluded in this system because it is almost impossible to develope the circulator which satisfies the specification of this system. Instead, phase adjasting system and fast PIN switch are empoloyed to cope with high VSWR. Therefore, high power klystron and microwave circuits of wide band are eagerly needed to develope for the LHRF system of INTOR.

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Lastly, we must note about a current drive which is extremely important for the future of a tokamak reactor. LHRF is so far the only one sheme which has demonstrated a current drive in tokamaks, though some problems are still under investigation. There are great possibility of the use of LHRF heating system to drive currents in INTOR. The engineering of LHRF which will be developed for the ion heating system is quite applicable to that for a current drive. If the frequency of the RF system in Fig. 8 is changed from 2.0 GHz to 3-4 GHz, it will be adequate for a current drive.

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References

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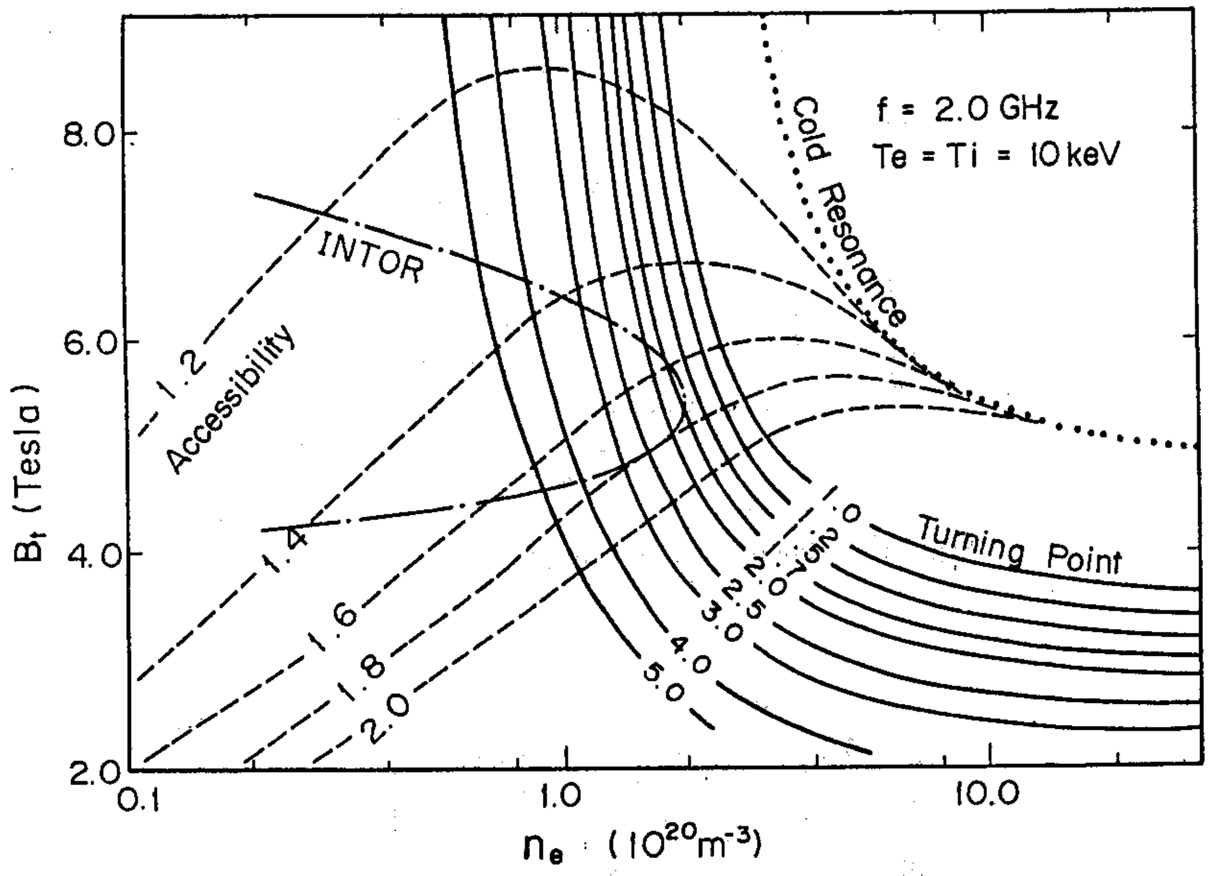

Fig. 1 Wave characteristics in plasma parameter space. The horizontal and vertical axises show the density and toroidal magnetic field, respectively. Dotted line of closed circles shows the cold lower hybrid resonance, solid lines the turning point from the cold LHW to the hot ion wave of each N_z-wave, dotted lines the accessibility condition (mode conversion point from slow wave to fast wave) of each N_z- wave. Mass number of ions is taken to be 2.4 (equal D-T mixture).

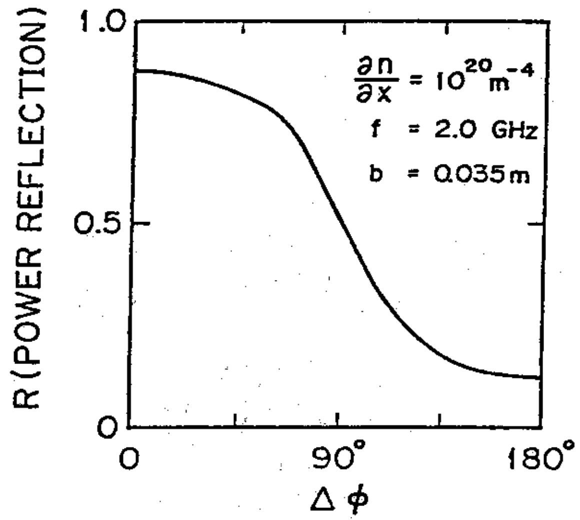

Fig. 2 Power Reflection coefficient vs Δϕ.

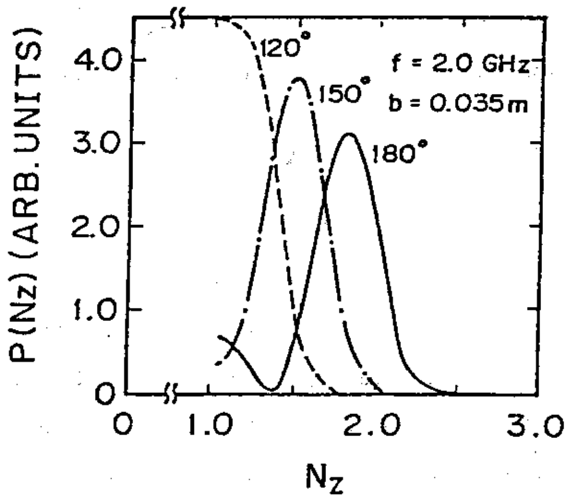

Fig. 3 Power spectrum of the radiated wave from the same launcher in Fig.2.

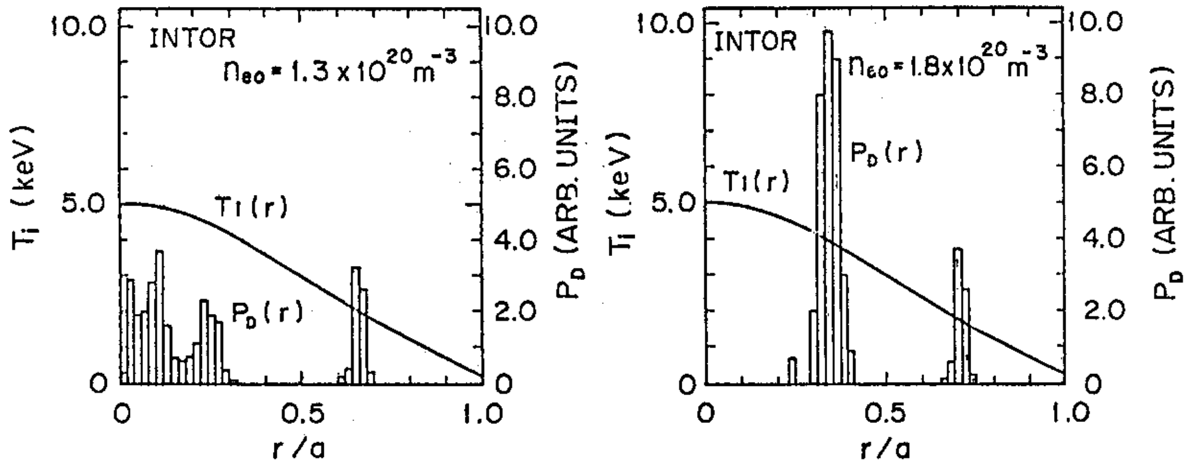

Fig. 4 Profiles of ion temperature and deposited RF power with (a) $n_{e0} = 1.3 \times 10^{20}$ m^{-3} and (b) $n_{e0} = 1.8 \times 10^{20}$ m^{-3}.

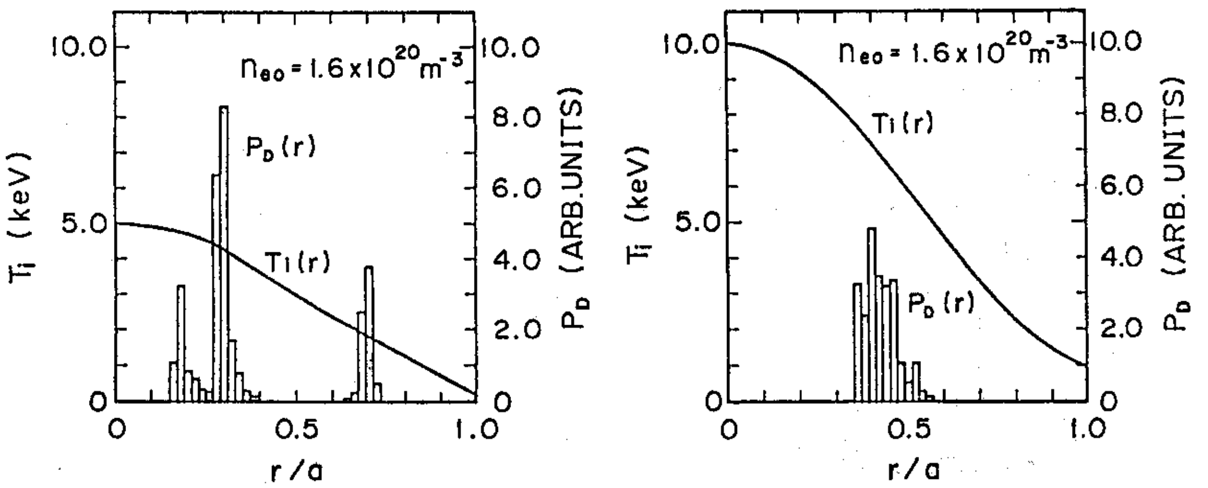

Fig. 5 Profiles of ion temperature and deposited RF power with n_{e0} = 1.6×10^{20} m^{-3}. (a) T_{i0} = 5 keV. (b) T_{i0} = 10 keV.

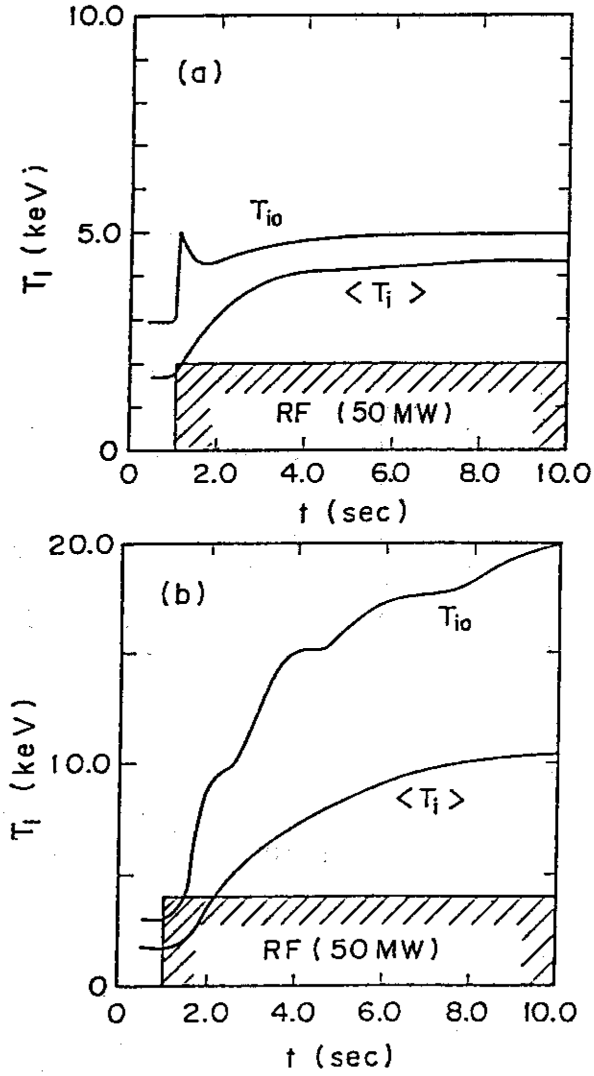

Fig. 6 Time evolutions of the ion temperature during the RF pulse in INTOR plasma in the cases of (a) linear model and (b) nonlinear stochastic model.

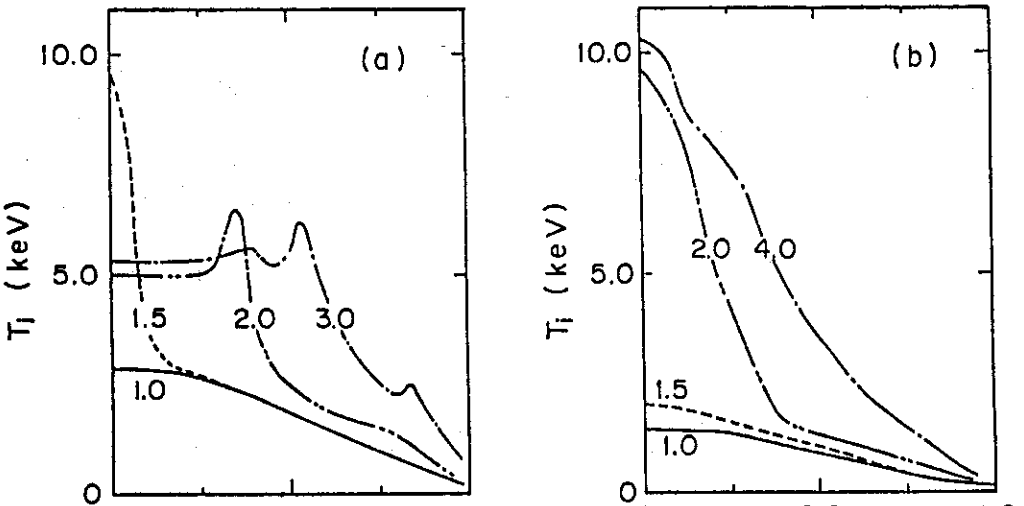

Fig. 7 Time changes of the profile of ion temperature. (a) Linear and (b) nonlinear stochastic model.

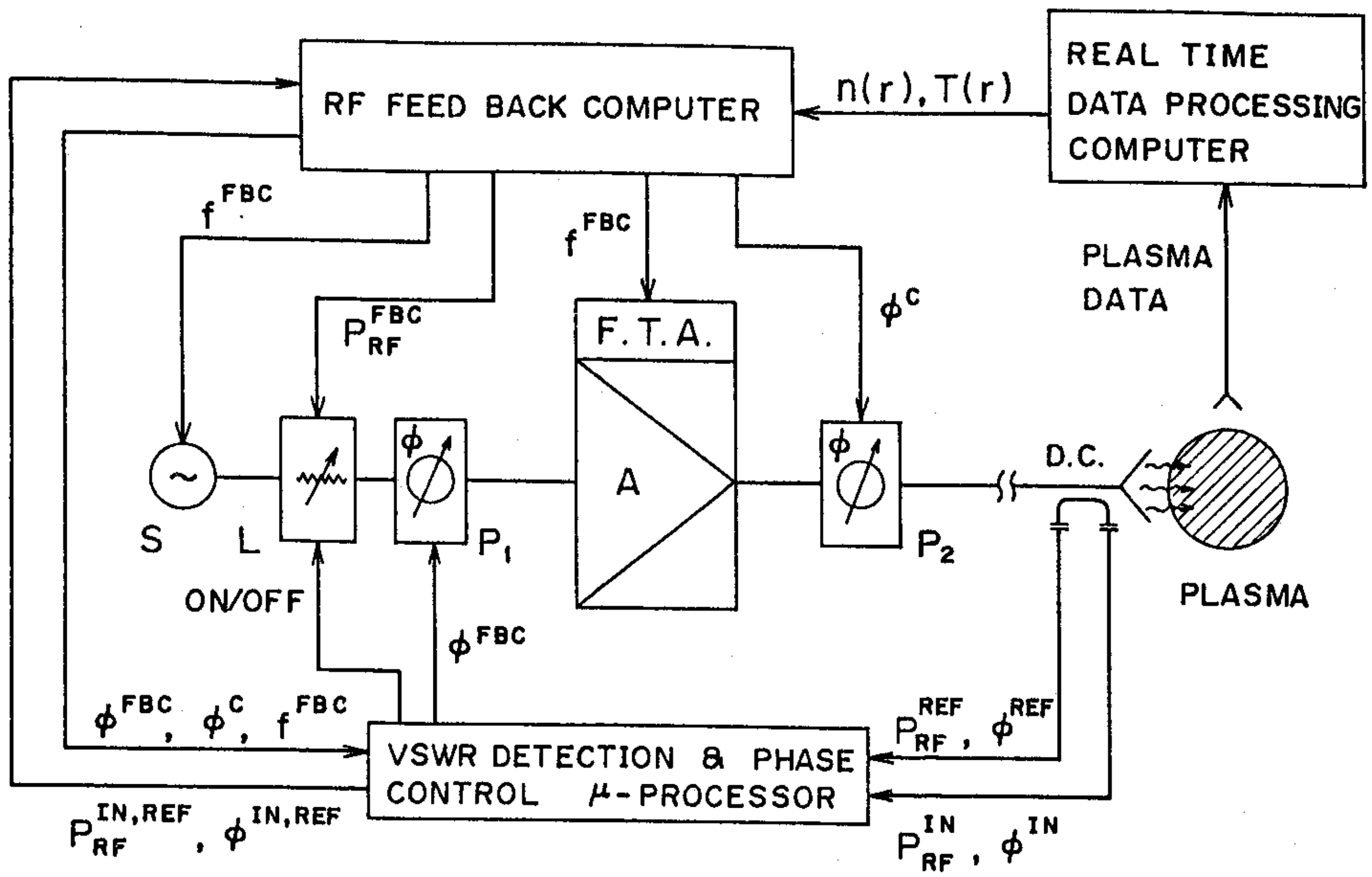

Fig. 8 Block diagram of the LHRF system for a large tokamak like INTOR. S : Signal Source, L : Level control and fast swich, P_1 and P_2 : Phase shifter of low power and high power sections, respectively, A : High power klystron amplifier, D.C. : Directional coupler, F.T.A. : Frequency tuning actuator. FBC denotes the feed back control signal.